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Improved Controller for High Temperature Super Conducting Magnetic Energy Storage (HTS-SMES)

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Abstract—**This paper describes a novel controller for a High Temperature Superconducting Magnetic Energy Storage (HTS-SMES) that can ensure (a) fast return of energy to the super-conducting coil under constant current mode and (b) a constant and sinusoidal input supply current irrespective of the varying load demand with and without harmonics. A special feature of this controller is its ability to smoothly charge the superconducting coil using constant current charging so that it can be ready for the next discharging operation as soon as possible. Analysis of the circuit operation under hysteresis control is presented in details. Simulation and experimental results are presented demonstrating the feasibility of the proposed power conditioning system.**

Keywords-smes; pcs; hysteresis; inverter; chopper; load leveling

I. Introduction

Because of their high efficiency and rapid response to power demand, superconducting magnetic energy storage systems (SMES) have been proposed for use in power system load leveling [1], power system stabilizers [2,3], fault current limiter [4, 5] and voltage support for critical loads [6].

The load leveling is particularly important, since the industrial load can be managed to reduce total electricity cost by maintaining a fixed maximum demand (MD) and power factor, while ensuring that security and reliability of the operation is maintained. Load leveling is performed by storing energy during off-peak periods when the price of electricity is lo and returning the energy during the peak period when the price of electricity is high. To achieve this, energy storage is usually required such as batteries or superconducting coils [7].

This paper proposes a novel control of a hybrid converter used in a high power High Temperature Superconducting Magnetic Energy Storage System (HT-SMES) consisting of a high temperature superconducting coil as the energy storage device and two power converters to provide the power conditioning system capability (PCS) when the SMES is connected to the utility system.

II. The Proposed HTS-SMES

The proposed HTS-SMES is shown in Fig. 1.

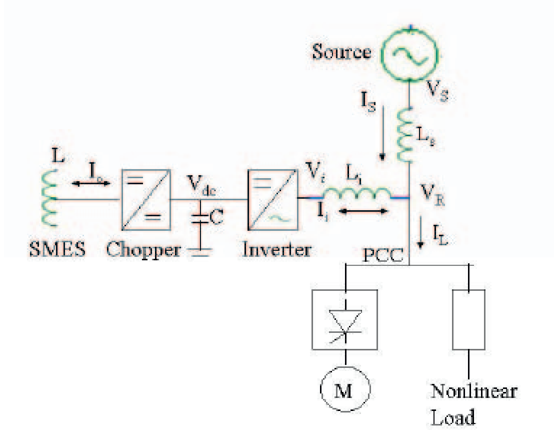

Figure 1. The topology for the proposed HTS-SMES.

Two hysteresis controllers are used. The first hysteresis controller ensures that as far as the power utility is concerned, the source current (I_S) appears as a constant sinusoidal load both in magnitude, phase and waveform, irrespective whether load (I_L) is distorted or varying in nature. This controller, therefore, performs several tasks, such as load leveling, reactive power compensation, active filtering and power control flow. The load leveling at industrial loads around few hundreds of kW loads can be justified by considering the maximum demand criteria and pay back can be calculated with the penalty imposed for violation of Maximum Demand (MD) and power factor. The second converter acting like a dc chopper interfaces the high temperature super-conducting coil with the dc link capacitor to control the energy in and out of the super-conducting coil. The chopper operates in order to keep the capacitor voltage (V_{DC}) maintained constant across the dc link. The DC link voltage reduces when load demand increases beyond the MD level activating the SMES to discharge to supply part of the demand and the DC link voltage increases when the load demand decreases below the MD level and energy is returned to the superconducting coil from the ac source. The controller therefore provides the necessary action for charging and discharging of the superconducting coil. In actual operation, the superconductor coil will have pulsated operation, which causes ac current losses in the coil. These

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losses must be taken into account while designing the SMES refrigeration system [8].

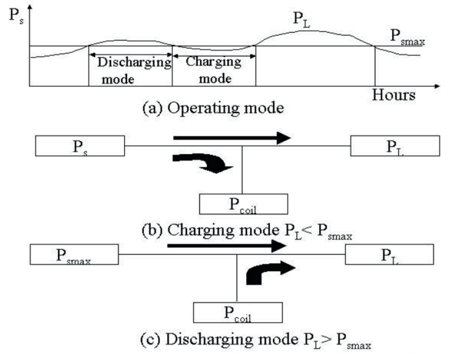


Figure 2. Operation under load leveling.

Hysteresis controller due to its inherent simplicity and many advantages is used to control each of the two controllers [9, 10]. The controller gives output signal ON/OFF when control quantity goes below or above the tolerance band of the reference value.

Under load leveling condition, if I_S is kept constant then the SMES coil current must meet the load demand variation. To utilize the maximum power flow through the network, the source current is maintained at its maximum rated value without violating the thermal limit. The controller ensures that the energy balance is maintained between source, load and SMES. The stored energy is regulated in controlled manner through the inverter and chopper. The role of the capacitor energy storage is to facilitate the direct exchange of energy from coil to the load. The power flow under load leveling is shown in Fig. 2.

III. THE PROPOSED CONTROL SCHEME

Preliminary simulation indicates the sensitivity of SMES current change with the variation in reference source current (I_s). When the reference source current is increased more than the load demand, the coil current increases and the superconducting coil is being charged, and when the source current is below the load demand, the superconducting coil discharges its stored energy to supply part of the load. A two-quadrant dc chopper performs this operation. The chopper keeps the dc bus voltage constant under the SMES operation. SMES coil charging current varies as the source current varies and it solely depends on the magnitude of the source current. The opportunity of regaining back the energy in the super-conducting coil in the shortest time is not feasible under this control operation.

Many schemes proposed in the past are based on this type of control strategy [11]. This leads us to the new proposal to modify the control strategy so that the recovery of lost energy can be regained in shortest possible time, by quickly changing the controller from voltage-mode control to current-mode control once the charging process is started.

While discharging, the controller is returned to voltage control mode again to regulate the DC link capacitor voltage. The switch over from current mode to voltage mode control of the chopper is decided by the polarity of the coil current.

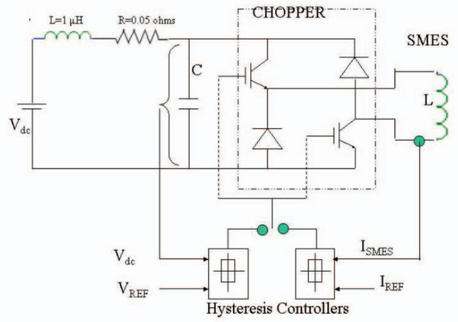


Figure 3. Chopper with current and voltage controllers.

This can be easily achieved by changing the algorithm inside the DSP and utilizing the same chopper circuitry. The coil is controlled using current control mode during charging and using voltage control mode during discharging. The switchover operation of the proposed circuit is simulated using the circuit shown in Fig. 3. Hysteresis controller is used to implement the current and voltage control.

The operation of SMES coil current using current control and voltage control mode is shown in Fig. 4(a). While charging under voltage control mode, it takes more time as compared to current control mode. This charging method ensures the readiness of the coil for the next discharge operation. While performing this task, the front end inverter is controlled to get the source current in phase with the source voltage.

The response of the coil current is faster in current control mode as compared to the voltage control mode. Fig. 4 (b) and (c) shows the dc bus voltage under constant current and constant voltage control mode respectively. The applied voltage across the coil is shown in Fig. 4 (d) and (e). The switching frequency is higher in voltage control mode as compared with current control mode.

The detailed control scheme integrating inverter and chopper controls with the power system is shown in Fig. 5.

IV. CONTROLLED PERFORMANCE

A simulation of the proposed controller has been carried out in SIMULINK (using power system block set) with detailed models of the inverter and chopper switches. The super-conducting coil current is varied from charging (40 A) to discharging (35 A). A variation in the load demand is used to achieve this. When the load is increased, the source current also increases to its maximum rated limit and the SMES current varies accordingly to compensate the remaining part of the demand. The simulation result in Fig. 6 shows that the coil is charged under constant current (stand-by mode) but during discharge the rate of coil current change is decided by the load dynamics. The source current is regulated to meet the load demand by the controller as long as the maximum limit has not been reached. Once the maximum limit of the source current is reached, the SMES coil provides the remaining load demand. Fig. 7 (b - d) shows the source, inverter and load currents indicating operation of proposed scheme. During the discharge process, the coil is discharging under constant dc bus voltage maintained by the chopper.

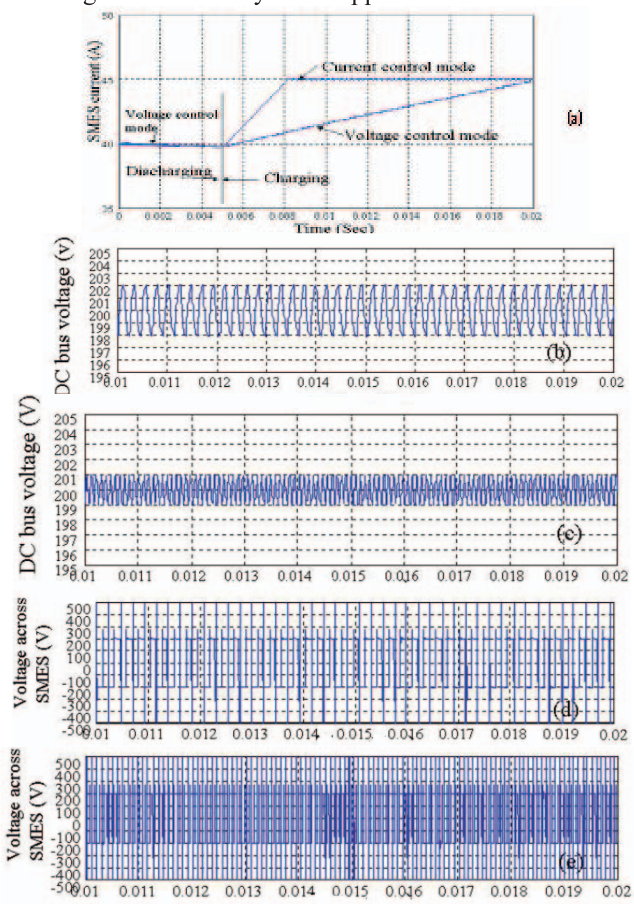


Figure 4. (a).SMES charging and discharging operation under constant voltage and constant current control mode, (b) DC bus voltage under constant voltage mode, (c) DC bus voltage under constant current mode, (d) Voltage across the SMES coil under current control mode, (e) Voltage across the SMES coil under voltage control mode.

V. Experimental Results

To verify the proposed scheme, a 2 kW three-phase inverter was designed and implemented in the laboratory as a bi-directional self-commutated voltage source converter and was used to interface the 380 V three phase supply system with the DC link capacitor. The power electronics switching devices used in the inverter employ the third-generation insulated gate bipolar transistors (IGBTs), each rated at 600 V, 50 A and connected in parallel with a reverse diode to give the converter the capability of handling power flow in reverse directions. The IGBT devices chosen have very fast switching speed and lower conduction and switching losses.

A DC chopper was also designed and implemented to interface the high temperature superconducting coil with the DC link capacitor. The test system parameters are given in Table I.

The controllers are implemented using DSP TMS320C31. The test results are shown in Fig. 8(a) and Fig. 8(b). The coil voltage and current are shown in expanded view in Fig. 8(a) -1 and Fig. 8(a)-2 respectively.

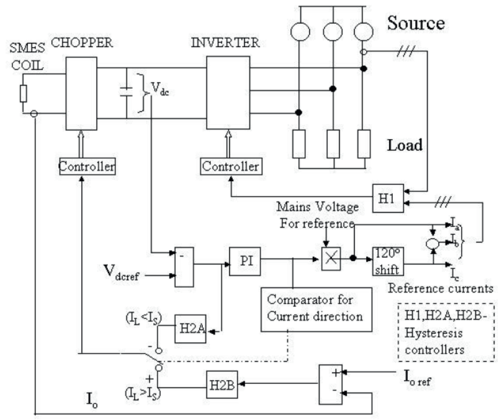


Figure 5. Control scheme of SMES base power conditioner.

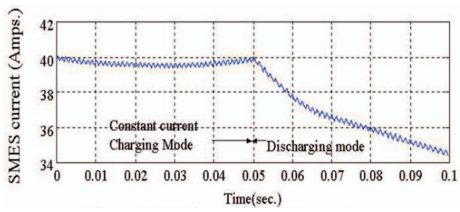
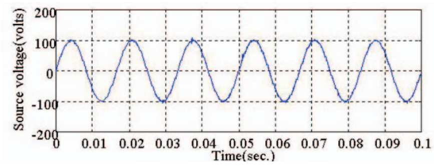
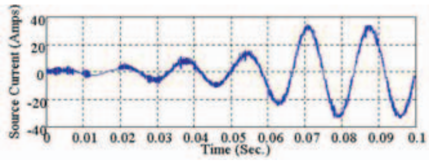


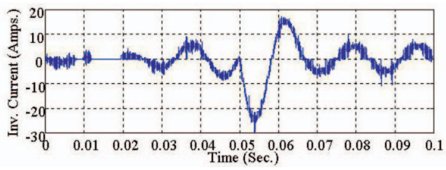
Figure 6. SMES charging and discharging mode.



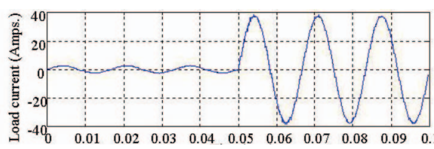
(a)



(b)



(c)



(d)

Figure 7. (a) Source voltage, (b) Source current, (c) Inverter current, (d) Load current.

TABLE I. PARAMETERS FOR EXPERIMENTAL SETUP

ac link inductance (L_s)	0.0016 H
dc link capacitor (C)	0.001 F
DC link voltage (Vdc)	200 Volts
SMES coil current (I_o)	10 Amps
SMES coil inductance (L_o)	0.12 H
Source voltage L-N (V_s rms)	100 V

This is in agreement with the simulated results shown in Fig. 4 (a) and (d). A constant current charging and discharging under constant voltage mode of SMES is shown in Fig. 8(b). The coil energy available to support the load (resistive and inductive) is very small in this experiment. The controller performance could be validated from this experiment. Fig. 9 also shows the source, load and inverter current along with the source voltage demonstrating the active filtering performance. The source current is in phase with the source voltage, while inductive load is supported. Further performance tests will be carried out with higher capacity SMES.

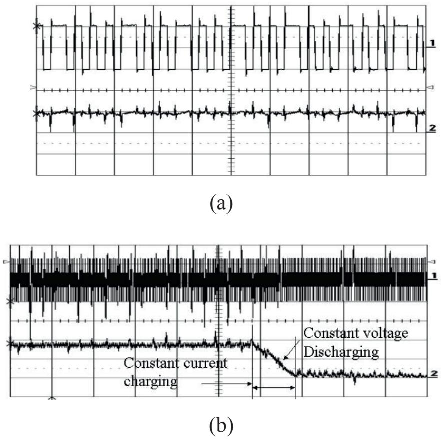


Figure 8. (a).1.Voltage across the SMES coil (200 V/div.) 2. SMES coil current (10 Amps/div), x axis - 0.5 ms/div, (b). 1.Voltage across SMES (400 V/div).2.SMES current during constant current charging and constant voltage discharging mode (5 Amps/div), x Axis- 0.2 sec./div.

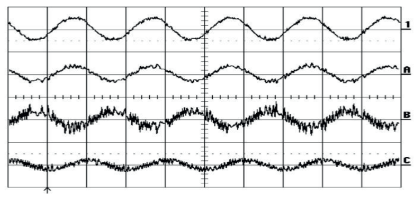


Figure 9. Active filter action while coil is charging. 1. Source voltage (200 v/div), A. Source current (10 A/div.), B. Inverter current (10 Amps/div), C. Load Current (10 A/div), x –axis - 10 ms/div.

VI. CONCLUSIONS

A modified controller with hysteresis band for a power conditioning system using high temperature superconducting magnetic storage has been analyzed and implemented in this paper. The use of a two-quadrant dc chopper in between the SMES coil and the dc side of the inverter allows charging and discharging in a very controlled manner. A new controller has been designed and implemented to ensure that the charging process can be made faster to ensure the readiness of the coil for the next operation. The effects of system parameters in the operation of the HTS-SMES are very important for the laboratory implementation of the micro HTS-SMES. The ratio of SMES inductance to source inductance, value of coil inductance and capacitor value at the dc link are important parameters in the HTS-SMES design. The proposed control scheme has been tested for its performance in a laboratory demonstration. The control scheme is very easy to implement and the results shows that such a system will be able to control the source current to be constant, sinusoidal in waveform and with unity power factor irrespective of the varying load demand and its harmonic content. During charging, energy can be returned to superconductor coil very quickly. The performance can further be improved by using modified hysteresis controllers with variable hysteresis band.

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